Recent short term global aerosol trends over land and ocean dominated by biomass burning

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Abstract

NASA's MODIS instrument on board the Terra satellite is one of the premier tools to assess aerosol over land and ocean because of its high quality calibration and consistency. We analyze Terra-MODIS's seven year record of aerosol optical depth (AOD) observations to determine whether global aerosol has increased or decreased during this period. This record shows that AOD has decreased over land and increased over ocean. Only the ocean trend is statistically significant and corresponds to an increase in AOD of 0.009, or a 15% increase from background conditions. The strongest increasing trends occur over regions and seasons noted for strong biomass burning. This suggests that biomass burning aerosol dominates the increasing trend over oceans and mitigates the otherwise mostly negative trend over the continents.

Popular Summary

Are aerosols increasing or decreasing over the globe?

This is a fundamental question. We know that CO2 and greenhouse gases are increasing. We've seen the "Mauna Loa" curves go up and up without end. Aerosols are thought to mitigate some of the warming expected of these increasing greenhouse gases. If aerosols increase at the same rate as the greenhouse gases we may have a steady-state where greenhouse gases act to warm the planet while aerosols cool the planet. There is no change and temperatures are constant. However, if aerosols are increasing faster than gases then we will cool the planet. If aerosols are increasing less fast than gases or even decreasing then the cooling will decrease and the planet will warm. There has been

speculation that the recent rapid warming over the past decade has been due to a decrease in global aerosol. There has been recent evidence that aerosols have indeed decreased over the past decade. This evidence is often very local in nature. It takes a satellite sensor to see the whole globe.

We use the seven year record from Terra-MODIS to look for trends in the aerosol optical depth. We find that aerosol has been undeniably *increasing* over the global oceans and the trend is significant at the 95% confidence level. More importantly if we look at the spatial and seasonal variations in the trend we see the complexity of the aerosol system. Biomass burning is increasing. Fossil fuel burning is decreasing.

To simply define aerosol forcing as the change in aerosol effects between pre- and post-industrial times is to ignore biomass burning which has nothing to do with industrialization and everything to do with population pressures on the environment. We can completely clean up our industrial sources and still be left with increasing aerosol from biomass burning. Most importantly, we conclude that we cannot reduce the complexity of the aerosol system as a monolithic global number that increases or decreases. We must treat aerosol at finer spatial scales.

This study is important because:

1. It contradicts the AVHRR record that shows aerosol over oceans *decreasing*. We point out the contradiction but do not attempt to reconcile the two sensors.
2. It shows the importance of biomass burning in influencing wide swaths of the oceans, and thus dominate global trends, despite strong decreases in aerosols over the northern industrial regions.
3. It shows that we can't reduce aerosols to the simple global numbers in the IPCC charts. They are much more complex.

Are aerosols increasing or decreasing? The answer is 'yes'. They are doing both. This paper goes beyond the simple IPCC global numbers to answer a complex question from a complex perspective.

IN REVIEW

Recent short term global aerosol trends over land and ocean dominated by biomass burning.

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Abstract

NASA's MODIS instrument on board the Terra satellite is one of the premier tools to assess aerosol over land and ocean because of its high quality calibration and consistency. We analyze Terra-MODIS's seven year record of aerosol optical depth (AOD) observations to determine whether global aerosol has increased or decreased during this period. This record shows that AOD has decreased over land and increased over ocean. Only the ocean trend is statistically significant and corresponds to an increase in AOD of 0.009, or a 15% increase from background conditions. The strongest increasing trends occur over regions and seasons noted for strong biomass burning. This suggests that biomass burning aerosol dominates the increasing trend over oceans and mitigates the otherwise mostly negative trend over the continents.

Greenhouse gases and aerosols are both active constituents of the Earth's atmosphere that affect the energy balance and the climate system, yet while greenhouse gases are long-lived and nearly homogeneous, aerosols are short-lived and heterogeneous [1]. For example, biomass burning aerosol emitted from fires is highly seasonal, occurring during dry seasons and exhibiting large interannual variability due to a combination of weather inconsistencies and changing cultural practices [2]. Urban/industrial aerosol also varies due to changing technology, economies, and population growth [3, 4, 5, 6]. We cannot characterize global aerosol trends from a few selected measurement points. Instead we must view changes over the entire globe.

Observations from satellite sensors enable us to characterize aerosol distribution over the planet [7, 8, 9, 10]. However, the sensors that produce the longest record of aerosol optical depth (AOD) were not designed to measure aerosol. Their long term records may not include retrievals over land (AVHRR) [7, 9], or may not measure in the midvisible spectral range (TOMS) [8]. The long-term records have been pieced together from different instruments flying on different platforms, often with drift in their times of observations. Even though these records have been carefully constructed and validated, it is preferable to analyze trends with an aerosol record derived from a single satellite sensor on a single platform. The MODerate resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra satellite began producing aerosol products in March of 2000 [10]. Unlike the earlier satellites with long-term records, MODIS was designed to retrieve aerosol information. It maintains a steady orbit with no drift in its equator crossing time, and especially important for trend studies, the instrument is calibrated with on-board calibration devices and monthly scans of the full moon. If there were calibration drift in the sensor's channels, these would be identified [11]. Furthermore, having two sensors on separate platforms provides a check on artificial trends arising from calibration drift. We would not expect to find similar AOD trends from both sensors due to calibration artifacts alone.

This paper analyzes the consistent seven-year Terra MODIS-derived aerosol optical depth (AOD) record [10, 12, 13], globally, over land and ocean separately to characterize areas and seasons of aerosol increase and decrease in recent years.

The data used in this study are the Terra MODIS daily and monthly Level 3 AOD, available on a 1 x 1 degree global grid [12, 14]. All data used in this study are aerosol optical depth (AOD) at 550 nm. The time series was constructed from seven full years of data that began with March 2000 and ended with February 2007, 84 months, corresponding to seven full 12-month years. We use full 12-month years to avoid artificial trends introduced by seasonal variability. The time series of the pixel-weighted monthly mean global AOD for land and ocean is shown in Figure 1. Error bars are based on measurement uncertainty as well as standard deviation of the monthly mean and number of grid squares included in the calculation.

The land and ocean global means show opposite trends. Aerosol optical depth over the ocean increases over the seven year record, while AOD over land decreases. The ocean trend suggests an increase of aerosol optical depth over oceans of 0.009 or approximately 7% over the past seven years (increase of 15% from background conditions [15]). If we assume each global monthly mean AOD is independent then the 84 months of data and the correlation coefficient of $R = 0.28$ produces a t-statistic indicating that the upward trend is significant at the 95% confidence level. In contrast the trend for the time series over land suggests a global decrease of AOD over land of 0.018 or roughly 9% over the seven year Terra record, although this trend is not statistically significant.

The *increasing* trend over oceans is a surprising result and contradicts the AVHRR record [16, 17]. We examined the ocean trend carefully and found that AOD increased in all seasons, although the trend was stronger in some seasons than others. The trend is not dependent on anomalous conditions in any particular year. If any 12 months of the data record are removed, the remaining 6-year record still has an upward trend, although the slope does vary depending on which year is missing. We note that the AOD in the Aqua data set also increases over ocean with the same slope (0.00011 AOD per month)[12], which rules out an artificial trend due to calibration drift. In no reasonable manipulation of the data were we able to find a *decreasing* trend in global mean AOD over oceans in the Terra-MODIS record.

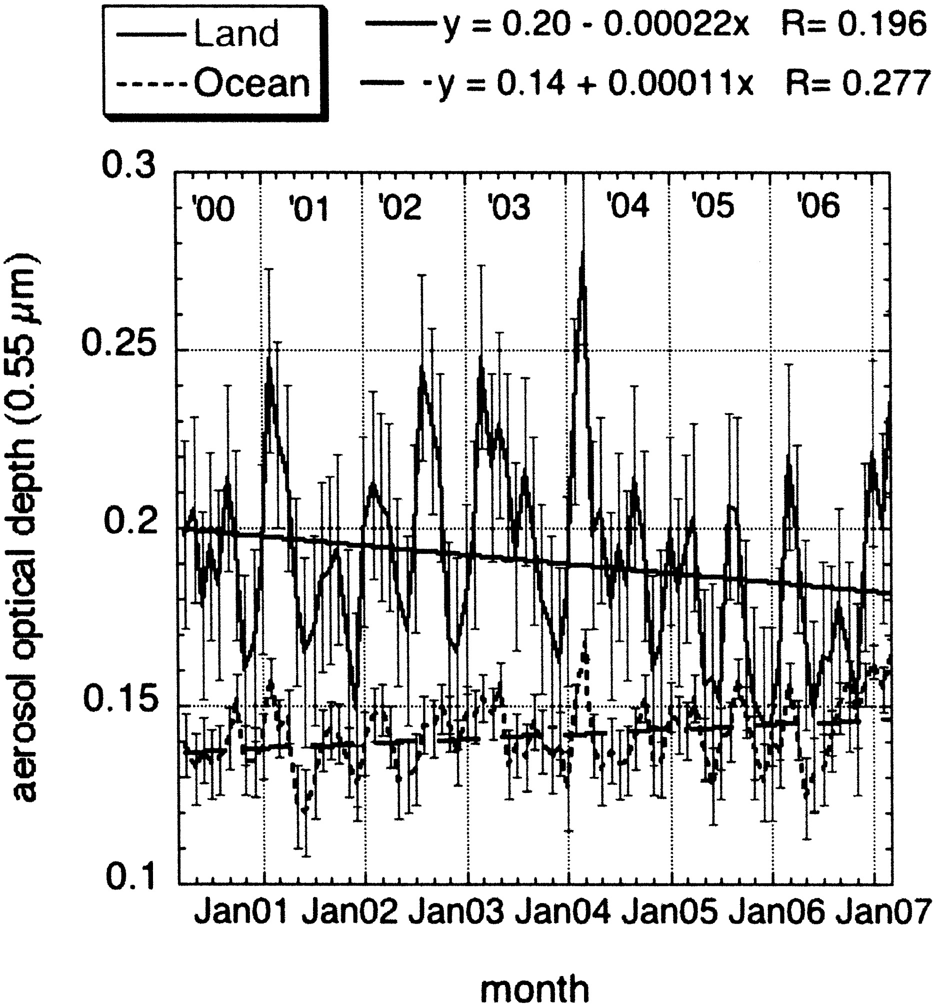


Figure 1. Separate land (solid-red) and ocean (dashed-blue) global monthly mean aerosol optical depth at 550 nm (AOD) with standard error plotted as a function of date. Data analyzed from pixel-weighted Terra-MODIS daily 1 x 1 degree square Level 3 products. Also shown are linear regression fits through each time series. The slope of the trend line for the ocean time series is significant at the 95% confidence interval. The trend for the land product is not significant.

Because aerosols are highly variable in time and space, we need to examine the trends spatially and seasonally. We calculate a linear regression and correlation coefficient through each time series, for each 1 degree square. The slopes of the linear regression are shown in Figure 2. Slopes can be either positive indicating an increasing trend over the seven year data record or negative, indicating a decreasing trend. Units are in AOD per month. The spatial patterns of strong slopes provide evidence that the reported slopes are based on physical processes and are not random noise.

Missing data occurs when conditions for a MODIS retrieval is not possible. For example, bright deserts, snow, low sun angle, etc, would cause missing data and reduce the number of available monthly means. In some grid boxes there were not sufficient monthly means to calculate the trend, in other cases missing monthly means contributes to the spatial inhomogeneity of the trends. When slopes in Figure 2 show no spatial cohesion such as the area around Antarctica, the trends in that region are not significant and should be disregarded.

Because aerosol loading in some locations is a seasonal event we wanted to see if significant trends occurred in particular seasons. The Level 3 data, described above was divided into seasons defined as March-April-May (MAM), June-July-August (JJA), September-October-November (SON) and December-January-February (DJF). Four subsets of time series are created from the monthly mean data, one subset per season, for each 1 degree grid square. Thus, for the seven year record, each subset time series consists of 21 months of data, unless a monthly mean was missing in a particular year for a specific grid square.

We calculate a linear regression and correlation coefficient through each seasonal time series, for each 1 degree square. The slopes of the linear regression for each season are shown in Figure 3. Units are in AOD per month, although to calculate total increase or decrease over the seven year period for that season, one would multiply by 21 and not 84 months. Figure 4 shows the latitudinal distribution of AOD and regression slopes for the four seasons, land and ocean separately, in addition to the total.

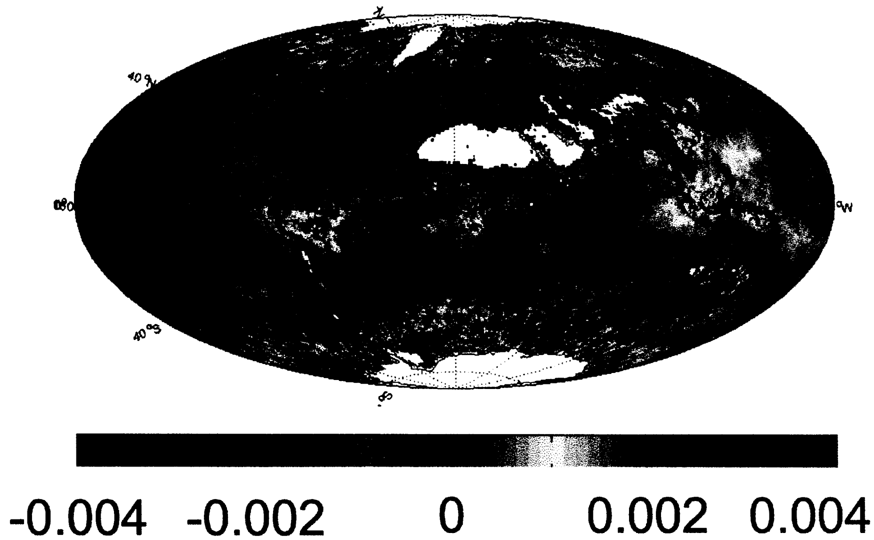


Figure 2. Aerosol optical depth (AOD) trends over the Terra record calculated from a time series of 84 monthly mean values. Trends are slopes of linear regressions of the time series fit for each 1 degree square independently. Units are in AOD per month. Yellows and reds indicate aerosol has increased over the seven years. Blue indicates aerosol has decreased.

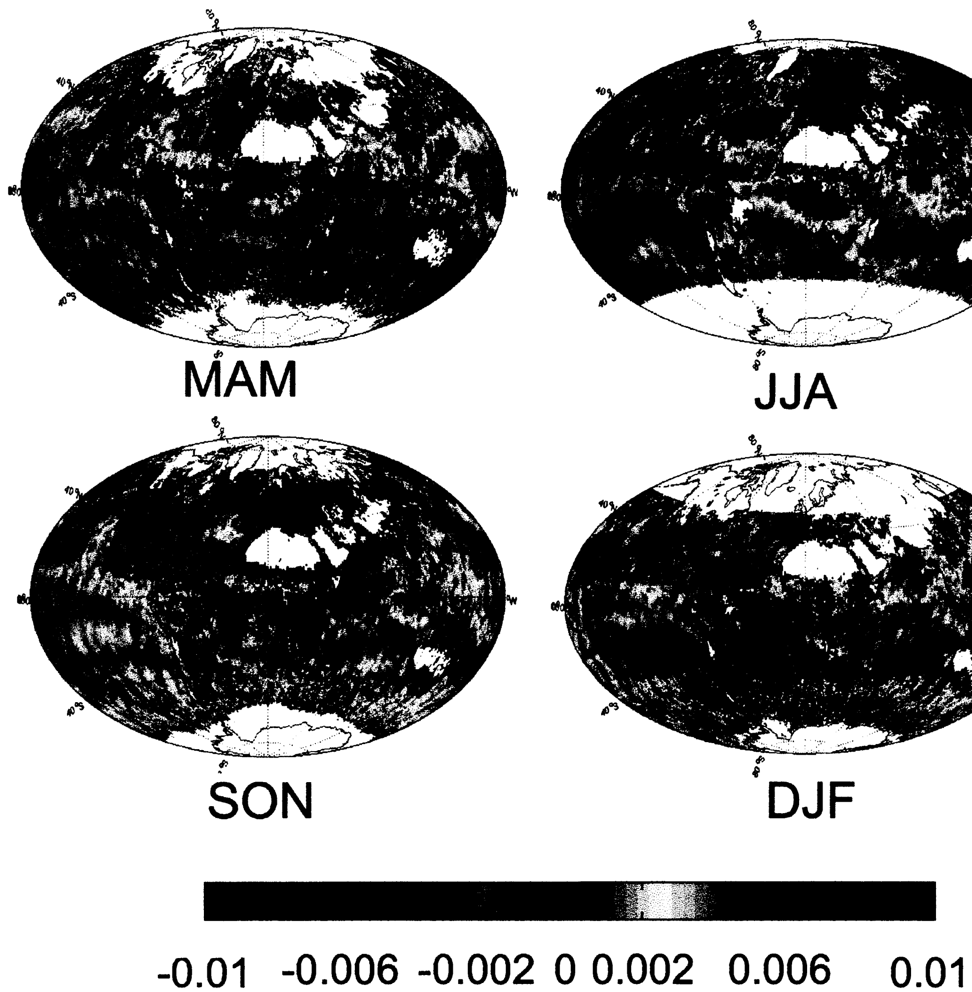


Figure 3. Aerosol optical depth (AOD) trends over the Terra record divided by season. MAM (spring), JJA (summer), SON (autumn), DJF (winter). All seasons defined by northern hemisphere. Trends are slopes of linear regressions of the 21 month time series fit for each 1 degree square independently. Units are in AOD per month of the season. Yellows and reds indicate aerosol increased over the period. Blues indicate aerosol decreased.

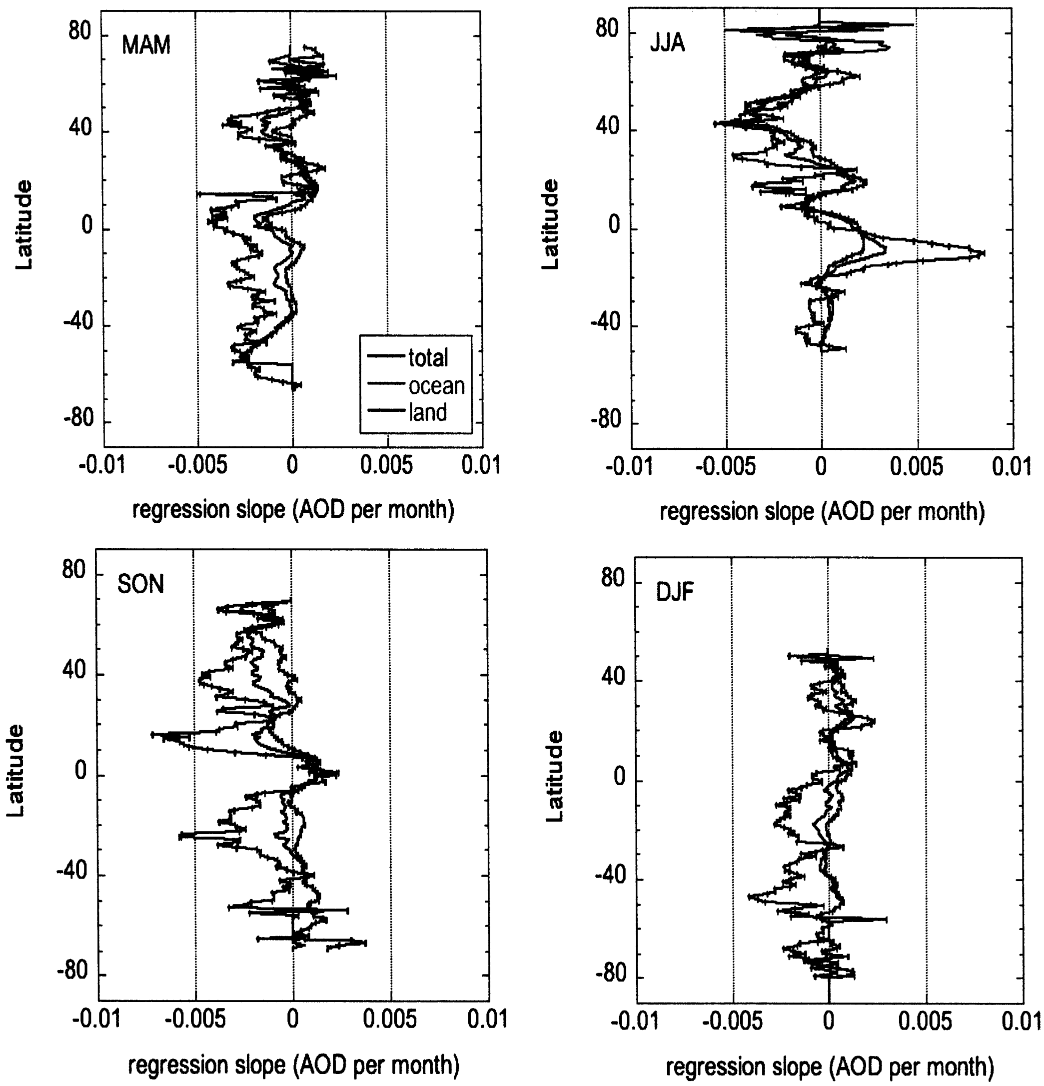


Figure 4. Latitudinal distribution of regression slopes for the four seasons as indicated in each plot. Land is plotted in red, ocean in blue and the total (land + ocean) in black. Standard error for each latitudinal mean indicated by error bars, but magnitude of the standard error is ~0.00001 and not easily seen.

In figures 2, 3 and 4, we see important trends in specific regions and seasons. In particular, aerosol is decreasing almost everywhere over land. The only major exceptions are tropical Africa during JJA, tropical South America during JJA and SON, Indonesia during SON and eastern Asia during MAM, SON and DJF. We note that all but eastern Asia are well-known biomass burning regions during the seasons indicated [18, 19]. There also appears to be increase of aerosol in certain boreal regions of Alaska and Siberia, also known for fires and smoke emissions [18, 19].

Over ocean the trends are mostly positive, with specific regions contiguous to noted biomass burning regions such as tropical Africa and Indonesia showing unusually strong positive trends in the proper season. The major exceptions to the overall positive trend over oceans include the southern circumpolar ocean and regions adjoining continents with strong decreasing trends during the season indicated.

Certain regions show increasing aerosol while other regions show decreasing aerosol, and much depends on the time of the year, which dictates different source activity, meteorology and transport. In general, the trends suggest that urban/industrial aerosol over continental regions has been decreasing over the past seven years, with the possible exception of eastern China in the Fall and Winter seasons. On the other hand, biomass burning, both in the tropics and in temperate regions appears to be increasing. The increase in biomass burning over the source regions may extend its influence across oceans as there is some evidence that the positive trend in oceanic AOD is being driven by increases in small particles [12]. Marine aerosol, dominated by large particle sea salt, is not a likely source of additional small particles.

It may seem contradictory that aerosol over land shows an overall *decreasing* trend, while transport from biomass burning from land to oceans is thought to explain the overall *increasing* trend over oceans. The decreasing land AOD trend is primarily a Northern Hemisphere phenomenon that drives global land trends because of the high proportion of land in the Northern Hemisphere. Likewise the strong biomass burning in the Southern Hemisphere affects global ocean trends because of the high proportion of ocean in the south. However, we acknowledge that attributing the oceanic increase of AOD to biomass burning is hypothesis that has not been proven.

For whatever reason the global mean AOD over ocean in the Terra MODIS time series is undeniably increasing from March 2000 through February 2007. Much of the oceanic increase is associated with the oceanic regions surrounding the Philippines and Indonesia. The biomass burning in this region is influenced by El Nino events that enhance the SON dry season in the archipelagos. The SON season of 2006 was an El Nino, and smoke production from Indonesia was very strong. However, the 2006-2007 El Nino was not stronger than the 2002-2003 El Nino, which occurred earlier in the Terra MODIS time series. Because the Terra time series spans two El Ninos, the increasing trend cannot be blamed entirely on an El Nino at the end of the time series.

Naturally a longer record spanning decades is highly desirable to determine whether aerosol optical depth is increasing or decreasing. However, trends associated with shorter

time series should also appear in the longer data record. The multi-decadal AOD trend in the AVHRR record contradicts the results found here over the period of overlap. Two differences should be noted. The AVHRR AOD is at 0.67 μm, while the MODIS AOD is at 0.55 μm, and the AVHRR record ends almost two years before the end of the MODIS record. The two time series overlap for only five years. MODIS is better calibrated and has greater consistency than AVHRR, and therefore should be better able to obtain the correct global aerosol trend. Further analysis is needed to understand why these two sensors suggest different trends of global AOD over oceans.

We note that either land-based or ocean-based studies acting alone, even if globally distributed may not represent the true global trend because we see that aerosol trends are highly spatially inhomogeneous and that land and ocean may produce opposite trends. Aerosol forcing simply cannot be treated in a similar manner as greenhouse gas forcing and must be evaluated at higher spatial and temporal resolution. [20]

References:

1 Y.J. Kaufman, Y. J., D. Tanre, and O. Boucher, *Nature*, **419**, 215, (2002).
2 I. Koren, L.A. Remer, K.M. Longo, *Geophys. Res. Lett.*, **in press**.
3 R. Harley et al., *Environ. Sci. Technol.*, **39** (14), 5356, (2005)
4 T. Novakov et al., *Geophys. Res. Lett.* **30**, L1324, (2003)
5 S.-W. Kim et al., *Geophys. Res. Lett.*, **33**, L22812, (2006)
6 D.G. Streets, Y. Wu and M. Chin, *Geophys. Res. Lett.*, **33**, L15806, (2006).
7 R. B. Husar, J. M. Prospero, L.L. Stowe, *J. Geophys. Res.*, **102**(D14), 16889 (1997).
8 J.R. Herman et al., *J. Geophys. Res.*, **102(**D14) 16911 (1997).
9 I.V. Geogdzhayev et al., *J. Geophys. Res.*, **110,** D23205 (2005).
10 L.A. Remer et al., *J. Atmos. Sci.*, **62**, 947 (2005).
11 B. Guenther et al., *Remote Sens. Environ.*, **83**, 16 (2002).
12 Supporting On-Line Materials
13 R.C. Levy et al., *J. Geophys. Res.*, **112**, D13211 (2007)
14 M.D. King et al., *IEEE Trans. Geosci. Remote Sens.*, **41,** 442 (2003).
15 Y.J. Kaufman et al., *Geophys. Res. Lett.* **28**, 3251 (2001).
16 M.I. Mishchenko et al., *Science* **315** (2007)
17 M.I. Mishchenko and I.V. Geogdzhayev, *Optics Express*, **15**, 7423 (2007)
18 G.R. van der Werf et al., *Atmos. Chem. Phys. Discuss.*, **6**, 3175 (2006)
19 L. Giglio et al., *Atmos. Chem. Phys.*, **6**, 957 (2006).
20 This work is indebted to the foresight of Yoram Kaufman who conceived and implemented the MODIS aerosol algorithms for specifically this purpose. The work was supported by the NASA Radiation Sciences Program, Interdisciplinary Research in Earth Science (06-IDS06-1) and Earth System Science Research (06-EOS/06-64) under the direction of Dr. Hal Maring.

Supporting On Line Material

MODIS Collection 005 aerosol products.

While Terra MODIS has the advantage of maintaining consistent hardware and orbital characteristics throughout its lifetime, it may not produce a consistent time series because of changes to algorithms. The MODIS algorithms including both the calibration algorithms that produce the radiances in engineering units and the aerosol algorithms that produce the geophysical products such as AOD, are constantly being evaluated and updated. Algorithm developers may at any time implement new code into the processing stream, creating an inconsistency in the time series. However, periodically the entire MODIS data record is reprocessed from beginning to end with consistent calibration and aerosol algorithms. After such reprocessing, the aerosol time series should be entirely consistent having been created from a single instrument, with a single sampling strategy, steady calibration and only one aerosol retrieval algorithm. Such a reprocessing was completed in early 2007 and labeled "Collection 005". The availability of Collection 005 allows us to evaluate trends in global and regional aerosol products for a seven-year period from March 2000 through February 2007.

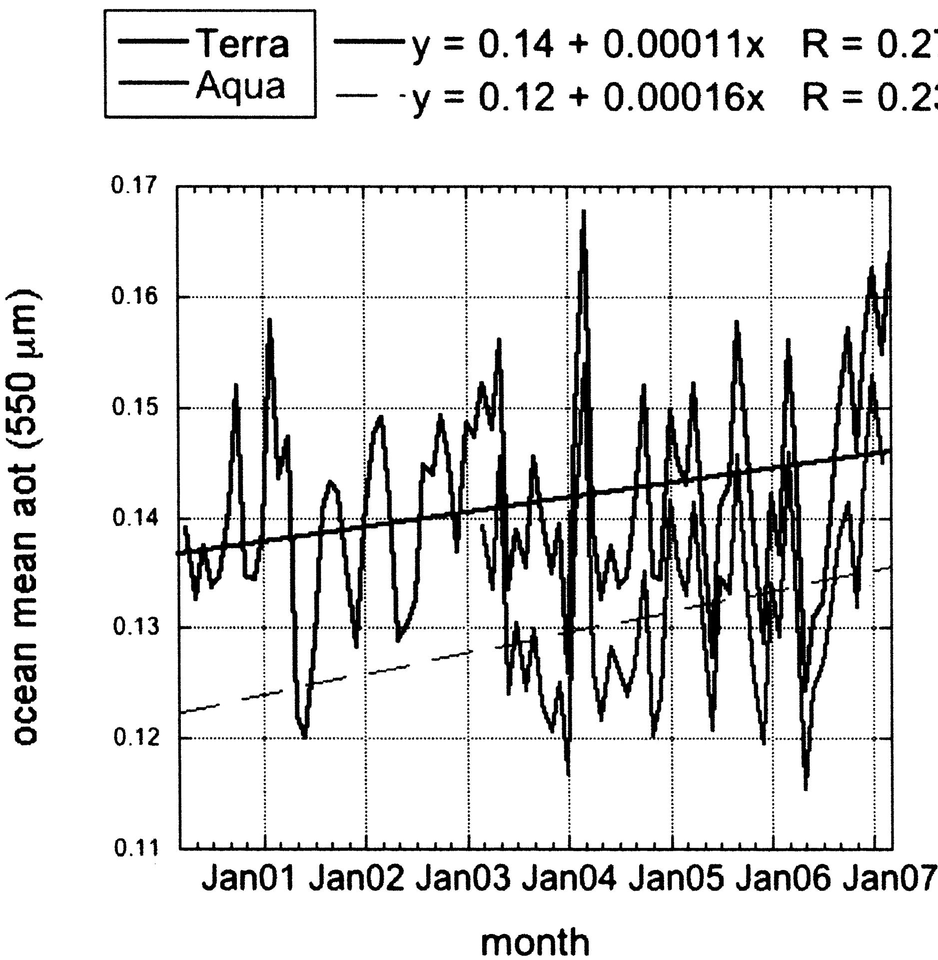
The parameter we use for the gridded analysis that provides the basis for Figures 2, 3 and 4 is the monthly mean Optical_Depth_Land_And_Ocean, [10,13]. In Collection 005 over land, only data with data quality flag (QA) greater than zero is included in this parameter. All poor data quality is automatically excluded. Over ocean, all retrievals are included no matter the quality flag. The reason for this is because of the conservative nature of the quality determination of the over ocean retrieval.

For the global mean analysis that produced Figure 1 we calculate the global mean from the separate parameters Corrected_Optical_Depth_QA_Land and Effective_Optical_Depth_QA_Ocean. These data are already weighted by the quality parameter. We calculate the global monthly mean from daily data and weight each daily value by the number of 10 km aerosol retrievals that were used to calculate that day's 1 x 1 degree mean. We use the pixel weighting in this situation to avoid anomalous independent retrievals and to better simulate the global mean had we used the original 10 km retrievals. Such "pixel weighting" strategy biases the global mean number to clear sky cases. In the context of this study, which is looking for overall trends in the global aerosol, such bias focuses our analysis to the aerosol itself and not to aerosol-cloud processes or phenomena.

Oceanic trend in Aqua-MODIS time series

Applying the same analysis method to the Aqua time series we find an upward trend in the oceanic AOD time series, of approximately the same magnitude as we find in the Terra data set. The Aqua time series spans only 60 months (5 full years). Because of the shorter data record the trend is not significant. There is an offset in the Collection 005 global AOD between Terra and Aqua. This is an offset that is currently under investigation. However, we see the same interannual variations in the Aqua time series

as we do in the Terra time series, and a similar increasing trend. Despite the offset, the two satellites share sufficient commonality to rule out a satellite-specific calibration artifact in Terra-MODIS causing the trend in ocean AOD seen in Figure 1.



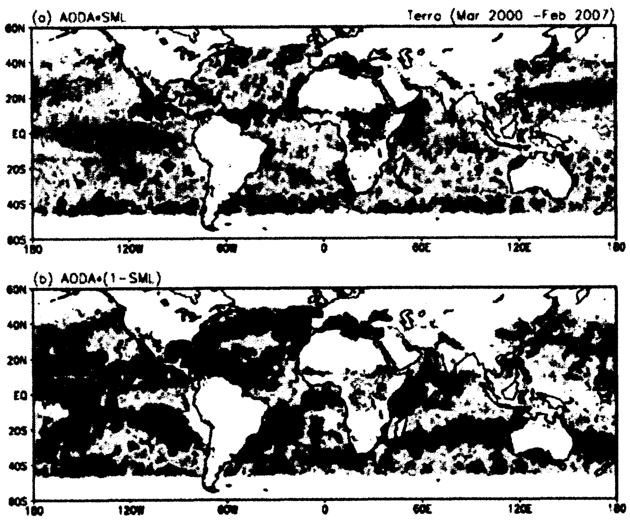
Trends in fine and coarse particle AOD

MODIS also produces an aerosol parameter referred to as the fine mode AOD. This is the contribution to the total AOD from the fine or small particles [10]. There is greater uncertainty in MODIS-derived fine AOD than in total AOD, and the parameter has not been validated. The uncertainty in fine AOD over land is especially large. Over ocean, the parameter is usable, although in clean regions of low total AOD uncertainty fine AOD can also be very high.

We analyze trends in fine AOD using a slightly different procedure than described above for total AOD. We again use 1 x 1 degree Level 3 data from Terra, but do not pixel-

weight the data to calculate monthly means. Then we run a 2 x 2 degree running average over the data because of the noise in this product, and calculate the trend of the fine AOD for each 2 x 2 degree box. Plotted below are the trends for fine AOD (top panel) and coarse AOD (bottom panel). Coarse AOD is the difference between Total AOD and fine AOD. In the plot below, red indicates significant positive trends at the 95% confidence interval, and blues indicate significant negative trends. Yellow indicates a positive and green a negative trend that is not significant. Significance was calculated using the Student's t-test statistic.

The plots indicate that much of the ocean regions are experiencing a significant positive (increasing) trend in the fine AOD. Coarse AOD appears to be mostly decreasing, but not significantly. Trends over land areas in these parameters are highly suspect due to the original quality of the parameter.

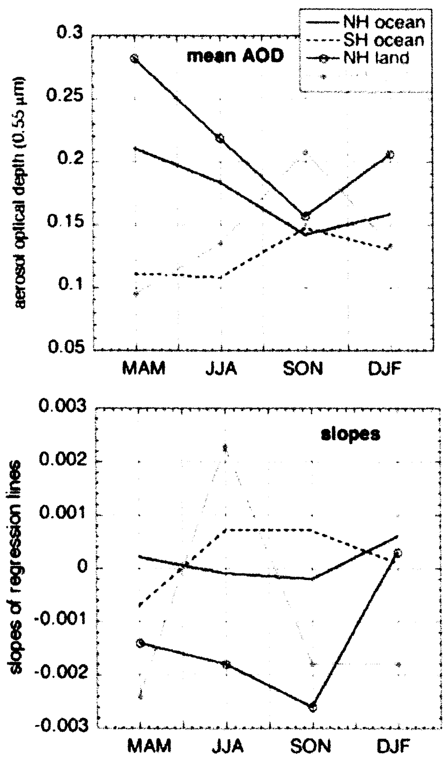


The trends shown in the figure suggest that the increase in total AOD seen in Figure 1 is an increase in fine particles. This may be because of an increase of biomass burning that is transported over oceans, or it may be an increase in oceanic biological activity that produces dimethylsulfide (DMS) particles. However, the plots show that the increase in AOD over oceans is unlikely caused by an increase in coarse particles such as marine sea salt or transported dust.

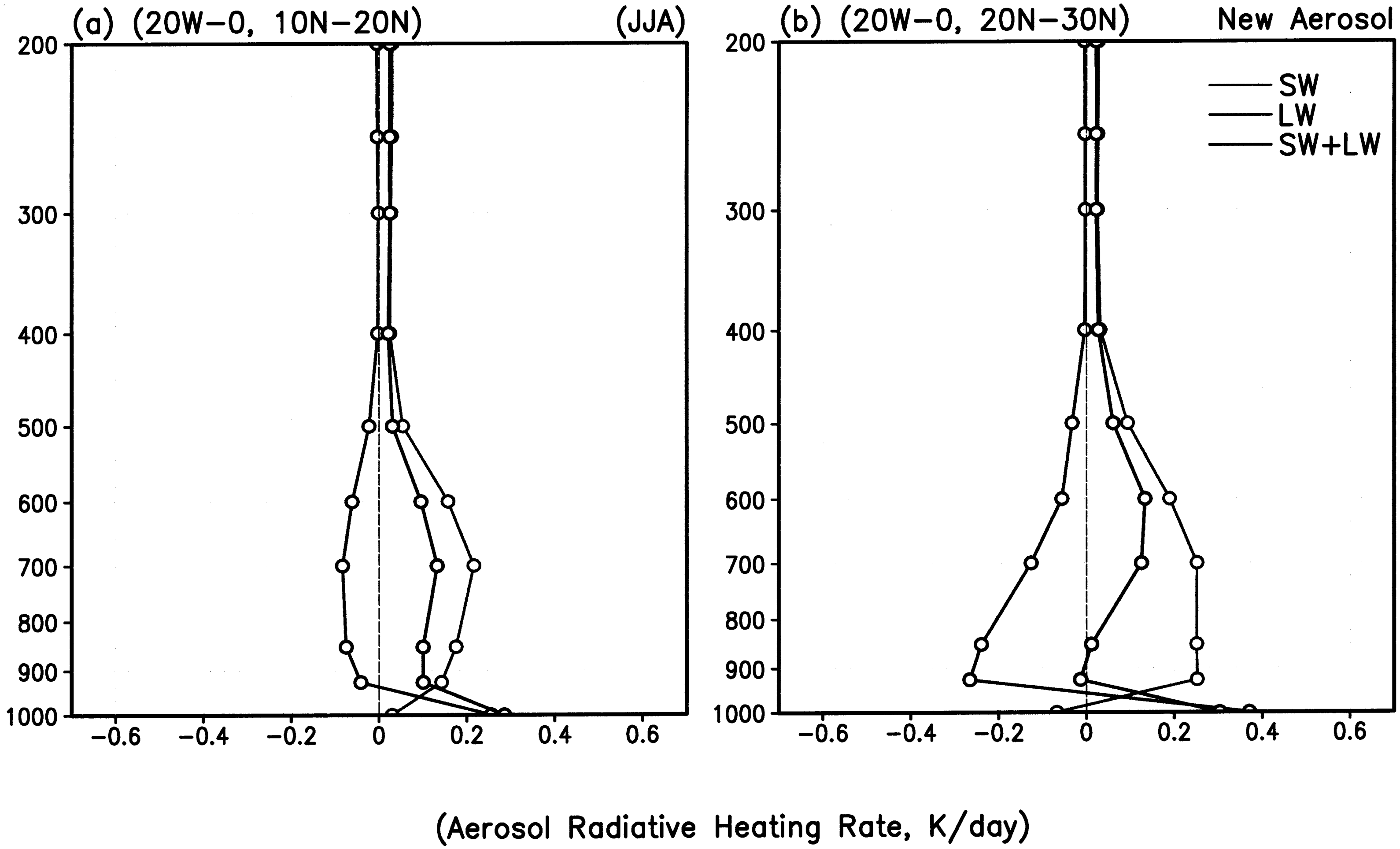
We do not want to over emphasize the results in this figure due to the relatively high degree of uncertainty in the retrieval of fine AOD, even over oceans. However, the results appear to be robust and add information to our analysis of total AOD.

Additional seasonal hemispheric figures

The regional/seasonal distributions of AOD trends are displayed in Figures 2, 3 and 4. Here we give two additional figures that summarize the seasonal and hemispheric division of the AOD and the trends.



The northern hemisphere (NH) has the highest mean AOD , both land and ocean, for every season except SON when the southern hemisphere biomass burning season is strongest. However the southern hemisphere's strongest increasing trend is JJA, which suggests a shift towards more burning earlier in the season or a latitudinal shift that follows the dry season. The positive oceanic trend is dominated by increases in the southern hemisphere. There is not a direct season by season relationship between increases over land resulting in increases over ocean. For example, the southern hemisphere ocean increase in SON has no corresponding increase over land in that season, as it does in JJA. Transport plays a major role in distribution of AOD over oceans. For example, biomass burning in Indonesia and the Philippines occurs in a very limited land area that may be statistically insignificant to hemispheric mean AOD over land. However the transport over surrounding oceans can dominate oceanic hemispheric means. The small ratio of land mass to oceans in the southern hemisphere allow for large concentrations of aerosols, originating from land sources, to be distributed over oceans. In the northern hemisphere, transport of aerosol the same distance from sources may more readily be distributed over land.



(a) (20W-0, 10N-20N)
(JJA)
(b) (20W-0, 20N-30N)
New Aerosol
SW
LW
SW+LW
200
300
400
500
600
700
800
900
1000
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
(Aerosol Radiative Heating Rate, K/day)